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EARTH ROTATION FROM LUNAR DISTANCES.(U)

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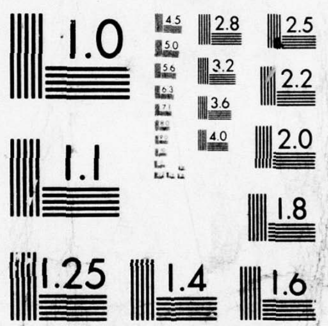

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THE UNIVERSITY OF TEXAS AT AUSTIN

DEPARTMENT OF ASTRONOMY

and

McDONALD OBSERVATORY

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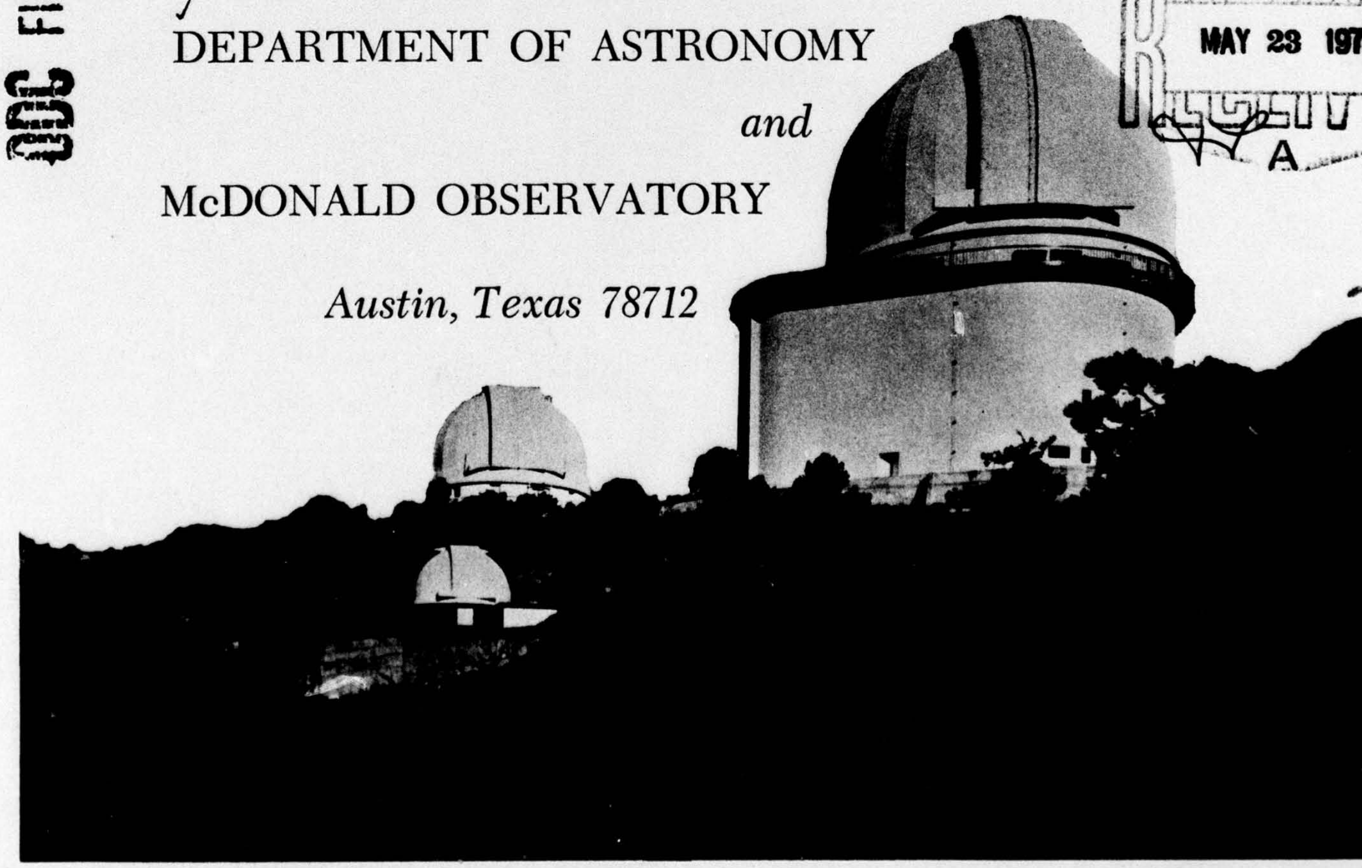

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(6) EARTH ROTATION FROM LUNAR DISTANCES.

FINAL REPORT

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Contract N00014-76-C-0641

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EARTH ROTATION FROM LUNAR DISTANCES: FINAL REPORT ON ONR CONTRACT

N00014-76-C-0641

I. Introduction: Background and Goals

A mathematical description of the orientation of the Earth's surface in space is conventionally broken into several distinct components: the precession and nutation of the Earth's angular momentum vector in inertial space, the motion of the instantaneous rotation axis of the crust relative to the angular momentum vector, the motion of the Earth's crust relative to the instantaneous rotation axis (or as one more commonly describes the *polar motion*, the motion of the axis with respect to the crust), and the instantaneous speed of rotation of the crust. These latter two phenomena are characterized by the Earth rotation parameters: the coordinates (x,y) of the pole, and the Universal Time UT1. The fine structure of the variation of these parameters is unpredictable, evidently controlled by internal geophysical processes that are not yet understood. The magnitudes of these variations are sufficiently large, however, to be critically important for many purposes, both technological and scientific. Foremost among the former is high-precision navigation, and among the latter positional and dynamical astronomy. Hence, it is an historic fact that the task of monitoring and extrapolating the observed rotation of the Earth has customarily been a collaboration between astronomers and maritime organizations. Within the

United States, the Naval Observatory (USNO) is charged with the statutory responsibility for maintaining accurate time and pole position information, which it does in collaboration with the Bureau International de l'Heure. Currently, these data are derived primarily from the photographic zenith tube (PZT) observations of USNO and elsewhere, with an important contribution in recent years from the Doppler Polar Motion Service (DPMS) of the Naval Surface Weapons Laboratory, at Dahlgren. DPMS gives only the coordinates of the pole, and it does not give more accurate values than the classical method, but it does have the advantage of being insensitive to weather and daylight, so that the data are much more densely spaced. For the past several years, there has been considerable discussion of the need to improve the accuracy with which the Earth rotation parameters can be determined on a regular service basis. It seems to be agreed beyond question that new instruments, and possibly new techniques, will be required to push the precision of determination significantly below the present level.

There are several techniques currently on the edge of availability which have the potential of contributing to such improvement. They include the advancement of the classical approach represented by the giant new PZT at USNO/Washington. They also include several techniques of an entirely new sort, based on highly sophisticated electronic technology: radio interferometry of celestial radio sources, laser ranging to artificial Earth satellites, and laser ranging to the Moon. None of these new techniques was developed with Earth rotation as a

primary goal. Nonetheless, following the axiom that "one man's noise is another man's signal", each of them involves observations of extraterrestrial targets with such high precision that they are extremely sensitive to the rotational position of the Earth, each of them showing theoretical promise of an order-of-magnitude improvement over the current time and polar motion service results.

The satisfaction of its responsibility for Universal Time and polar motion requires that USNO Time Service Division maintain a high level of awareness concerning technological developments in the determination of these parameters. They are, of course, heavily involved in improvements to the classical methods, and they have recently decided on a pilot project in radio interferometry. Personnel limitations prevent that they be active in all new areas, however. Their close relation with NSWL insures that they are well-informed, have access to the data, and can influence the direction of artificial satellite techniques. In the past, there has been no such interaction with lunar laser ranging, despite the fact that it is the first of the new techniques for which one has attempted to organize a pilot demonstration in an Earth rotation service bureau mode. Thanks to the advocacy of Dr. G. M. R. Winkler, Director of Time Service Division, this contract was undertaken to pursue the following scientific goals: a) to evaluate the accuracy of Earth rotation parameter determinations from the "existing network" of LLR stations; b) to investigate the optimum location for any additional stations that might be required to meet the future needs of Time Service Division; and

c) to construct computer software for the extraction of Earth rotation parameters, and the verification of that software using real multi-station data. An administrative task that occupied very little time, but was nonetheless important, was the world-wide coordination of the preparations for the EROLD observing campaign. This report is a summary of the activities under this contract during the calendar years 1976-77.

II. Personnel

The activities funded under this contract were performed entirely by the Principal Investigator, occupying 9.5 manmonths during the 2-yr period. Some aspects were done in collaboration with lunar laser personnel at the University of Texas at Austin, and with Dr. O. Calame at BIH/CERGA.

III. Influence of Station Location on Earth Rotation Accuracy

This study adopted the basic working hypothesis that Universal Time and polar motion are to be determined using only LLR data. The three fundamental questions that were asked were a) with what accuracy can the "existing network of LLR stations be used to determine these parameters; b) are additional stations needed to satisfy the requirements of a time and polar motion service; and c) where should such stations be located?

In discussing the accuracy obtainable, it is first necessary to define the observational network to be used. In the preceding paragraphs, I have used the phrase "existing

network", and the quotation marks are meaningful. Operationally, the largest current problem is that the existing network does not yet in fact exist as a network. At present, there are seven lunar laser facilities: one each in Australia, France, Germany, Japan and the Soviet Union, two in the United States (Hawaii and Texas). At the moment, five of them have fired at the Moon, four have received echos, two have confirmed observations, and only one is operating satisfactorily; four of them are more than a year behind schedule in becoming operational. It is a difficult technique. Based on an admittedly subjective (but defensible) evaluation, it seems reasonable to restrict one's attention to a maximum 4-station "existing network", utilizing stations in Texas, Hawaii, Australia and western Europe (France and Germany are geometrically nearly equivalent, so those two will be taken to be a single station, somewhat less prone to weather and technical problems than the others).

The capabilities of this network have been examined by means of a classical covariance study, built on the techniques and software previously discussed in the open literature (ref. 1-4). Without giving the details, it was found that, with the satisfaction of one important condition, any three of these stations operating on a given day are capable of determining all three Earth rotation parameters with an accuracy better than the accuracy with which the Earth-Moon distance is measured. Since the goal of the LLR network is three-centimeter accuracy in the lunar range, this represents an order-of-magnitude improvement over the capabilities of the present time and polar motion services. The all-important

condition is that at least one of the stations must be in the opposite hemisphere from the Moon; if this is not so, then the pole position determination will be degraded, although it will still be somewhate better than with the current classical technique. These results are in substantial agreement with those presented by Stolz and Larden (ref. 5) at the SALUR symposium, while the present study was still in progress.*

At first glance, this result would seem to indicate that the answer to the second question is negative, that no additional stations are required. This ignores the fact that the weather in southeastern Australia is not strongly correlated with the lunar orbit; there will be many instances when the Moon is at northerly declination and the only existing southern hemisphere station will be out of service due to weather (or other reasons!). What is worse, with only four stations, there will be a significant number of times when at least two will simultaneously be out of operation. The station that is probably least susceptible to weather loss is Hawaii, but it is also the least powerful for the determination of the pole position, because of its low latitude. The Texas station has favorable weather also, but it is not yet known when the existing system will be upgraded to 3-cm. It seems clear that, if polar motion is to be determined from LLR data, there must be more stations, and their siting should be done on the basis of maximum benefit to the determination of the pole

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*In fact, it seems that Stolz began that study upon seeing a copy of a proposal by the present writer.

coordinates.

All presently-envisaged LLR sites are approximately equally useful for the determination of Universal Time. The sensitivity of (x,y) determination is, however, critically dependent on the zenith distance of the Moon at meridian transit. Following the techniques of Silverberg et al (ref. 3), the sensitivity analysis indicates that the best combinations of pairs of stations for this purpose are those that share the same longitude and are separated by a large latitude difference.* The latitude may not be arbitrarily high, however, because the accuracy obtainable in tracking the Moon itself begins to degrade for stations at latitudes higher than about 50°. This is because the Moon is lower on the horizon at meridian passage, and the hour angle arc described between moonrise and moonset is correspondingly smaller. Thus, for example, the best complement to the Texas site lies in a strip around 105° west longitude, from 30 to 45° south latitude.

There is another type of constraint that does not appear in a mathematical analysis, but which must have a profound influence on one's interpretation of the results; this is the constraint of geography. The mathematically-preferred site is in the open ocean. Consequently, one is less interested in the most favorable site from the mathematical point of view than in the most favorable site that is in fact feasible. Mapping the area around 105° west longitude for the effect of coupling with the McDonald Observatory as a 2-station pair, one finds that the west coast of

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*This similar to the siting of the 2nd USNO PZT at Richmond, Fla., on the same meridian as Washington.

Chile (about 75° longitude) is not much degraded from the optimum open-ocean solution. There is, in fact, already a U.S. astronomical facility within this zone: the InterAmerican Observatory unit of the Kitt Peak National Observatory, at La Serena, Chile. If an additional U.S. station is to be constructed for polar motion observations, then this would appear to be the most desirable location.

La Serena has the additional attraction of being on the "stable" side of the most active tectonic plate subduction zone in the world, which would make it a valuable control point for measurements of the motions in the Nazca and Pacific plates.

IV. Computational Software for EROLD

The second major effort under this contract was the construction and verification of computer software adequate to determine Earth rotation parameters from LLR data. The construction of this software has been accomplished using the methods and principles described by Calame (ref. 1) and Mulholland (ref. 2). It was not necessary to begin *ab initio* with this task; indeed such a procedure would have been both extremely inefficient and much too time consuming for the time scales involved. The software was constructed by making important modifications to pre-existing programs that had been constructed for other applications of laser observations. As of the end of the contract performance period, the software had been completed, and to all appearances it was working correctly. Unfortunately, it has not

yet been possible to submit it to the final test, multi-station data.

No matter what technique is used, any one station can at most determine two components of the three-dimensional rotation of the Earth, and these two components are not directly the parameters desired. Each station can determine an apparent variation of its latitude (the component of polar motion along the meridian of the observatory) and an apparent rotational position of the Earth (UT0) corresponding to the assumption that the component of polar motion transverse to the meridian is zero. Both of these parameters are functions of all three of the Earth rotation parameters sought, as well as of the coordinates of the observing station. Thus, it is necessary to combine the observations from at least two stations in order to obtain the desired quantities. Obviously, a complete checkout of the computer software cannot be performed until adequate date from more than one station exist. In this context, "adequate" means data that cover an arc of several hours during a given day, preferably symmetric about the meridian.

At the moment, the only station that has ever produced "adequate" data is the McDonald Observatory. Thus, for reasons totally beyond the control of this contract, the computer software has not yet been verified on real multi-station data. It seems unlikely that serious problems will arise when such data exist, but this remains to be seen.

V. EROLD Coordination

During the span of this contract, the PI was the coordinator for the observing campaign that was to have begun determination of the Earth rotation parameters, beginning on 1 January 1977. Due to startup delays at the stations, this campaign has not yet begun in any meaningful way. Nonetheless, The data transmission, processing , and disemination channels are all well established, and we are only waiting for the observers to produce observations.

VI. Subsidiary Documentation

Partial results of the work performed under this contract have been published, and the following documents are included by reference as parts of this final report:

J. D. Mulholland (1977), "Mathematical Modelling of Lunar Laser Range Measures and Their Application to Improvement of Physical Parameters", in *Scientific Applications of Lunar Laser Ranging*, (Reidel, Dordrecht), p. 11.

J. D. Mulholland and O. Calame (1978), "Earth Rotation From Lumar Distances: Basis and Current Status", in *Proceedings of the 1977 Planning Meeting for Precise Time and Time Interval*, in press.

P. J. Shelus, S. W. Evans and J. D. Mulholland (1977), "Earth Rotation as Inferred from McDonald Observatory Lunar Laser Observations during October 1975", in *Scientific Applications of Lunar Laser Ranging*, op. cit., p. 191.

E. C. Silverberg, P. J. Shelus, J. D. Mulholland and G. L. Loumos

(1976), "An Estimate of the Geodetic Accuracy Obtainable with a Transportable Lunar Laser Station", *Bull. Géodésique* 50, 331.

VII. Concluding Remarks

It had been our wish to extend the sensitivity study to more realistic cases, and especially to test the computer system on real data; neither of these was possible, due to a variety of reasons, budgetary and technical.

The system presently used for the routine determination of Earth rotation parameters, Universal Time and the coordinates of the pole, uses a mixture of several different types of observation. This system will be replaced in the not-too-distant future by a new system based on new techniques. The present study has been undertaken on the assumption that such a system can be built on lunar ranging along. Indeed, that assumption seems to be warranted. Can and will are often quite different, however. It seems very likely that the future system, as the present one, will consist of a mixture of different techniques. In my opinion, however, the best mixture can only be found after each of the techniques involved has been tested independently, to discover its strengths and weaknesses. I view what has been accomplished under this contract as a useful step in that direction.

VIII. Acknowledgements

Many people have contributed in one way or another to this project. The secretarial contributions of Nora Otto have been vary satisfying and helpful. My various collaborators have

been very helpful, and usually agreeable. I acknowledge with thanks the encouragement and support that I have received from Dr. G. M. R. Winkler, U. S. Naval Observatory, and from Dr. L. Larmore and Mr. J. G. Heacock, Office of Naval Research.

IX. References

1. O. Calame, *Manuscripta Geodaetica* 1, 173, 1976.
2. J. D. Mulholland (see section VI).
3. E. C. Silverberg, P. J. Shelus, J. D. Mulholland and G. L. Loumos (see section VI).
4. P. J. Shelus, S. W. Evans and J. D. Mulholland (see section VI).
5. A. Stolz and D. Larden, in *Scientific Applications of Lunar Laser Ranging* (Reidel, Dordrecht), p. 201, 1977.